Venous flow and pressure

Seshadri Raju MD, FACS
The Rane Center
Jackson, MS.

Disclosures

• Stock in Veniti inc.
• US patent IVUS diagnostics in CVD
• US patent venous stent design.
• Stent usage in iliac-femoral veins is currently off label.

Poor compliance affects bending regimen more than the stretching

Venous pressure increases if the caliber is smaller (local or diffuse stenosis) or the flow is increased (A-V fistula). Normally, limb flow is a fixed fraction (11%) of cardiac output.

When outflow exactly equals inflow, the water level will be stable (black line). When inflow is restricted (stenosis), water level/pressure rises (red line) and overflow (collaterals) occurs. When the dam is removed (stented), arterial inflow is same, but venous pressure falls.

Optimal post-stent caliber in iliac vein stenting derived from IVUS planimetry/Poiseuille Law/Murray's Scaling Law.
Normal Acute Moderate DVT Acute Phlegmasia Chronic PTS

11 mmHg

24 mmHg

100 mmHg

19 mmHg

26 mmHg

100 mmHg

17 mmHg

100 mmHg

217 mmHg

100 mmHg

217 mmHg

100 mmHg

268 mmHg

100 mmHg

268 mmHg

100 mmHg

14 mmHg

Collateral Efficiency ≈ Conductance
Conductance ≈ 4^{th} Power of Radius (Poiseuelle)

Even if collaterals are large, it is unlikely there will be enough numbers needed. Collaterals alone are unlikely to normalize pressure.

The Poiseuille Equation

\[ F = \Delta P \times \pi / 8 \times 1 / \eta \times r^4 / l \]

The geometric factor ≈ Conductance/Resistance

Number of collaterals needed to keep peripheral venous pressure normal. Less number will elevate peripheral venous pressure.
The Effect of Compliance on Conduit Volume (mL)

<table>
<thead>
<tr>
<th>Penrose Wall Thickness</th>
<th>Bending Regimen Volume*</th>
<th>Stretching Regimen Volume @ 20 mmHg</th>
<th>Total Conduit Volume</th>
<th>Ratio Bending / Stretching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ply</td>
<td>12</td>
<td>7</td>
<td>19</td>
<td>5 : 1</td>
</tr>
<tr>
<td>Two Ply</td>
<td>21</td>
<td>9</td>
<td>30</td>
<td>2 : 1</td>
</tr>
<tr>
<td>Three Ply</td>
<td>19</td>
<td>12</td>
<td>29</td>
<td>1 : 1</td>
</tr>
<tr>
<td>Four Ply</td>
<td>11</td>
<td>8</td>
<td>19</td>
<td>1 : 1</td>
</tr>
</tbody>
</table>

* Unstretched Volume
** Stretched Volume

The caliber, not the number is the main factor in collateral efficiency. The tibial veins have many collaterals of equal caliber.
The femoral vein and IVC often enlarge embryonic collaterals to large size. The bottle neck is the iliacs which have only tributary collaterals with reverse natural flow.

Note there is no threshold %value of 'critical' stenosis in veins.

Diameter Estimates of for the iliac-femoral vein segments derived from various methods.

<table>
<thead>
<tr>
<th>Vein Segment</th>
<th>From Distribution Curve of IVUS Area in Patients (n=346)*</th>
<th>Poiseuille's Law</th>
<th>Young's Scaling Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIV</td>
<td>17</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>EIV</td>
<td>15</td>
<td>N/A</td>
<td>15</td>
</tr>
<tr>
<td>CFV</td>
<td>N/A</td>
<td>N/A</td>
<td>12*</td>
</tr>
</tbody>
</table>

- *With a Z-Score of greater than 1.65; see text
- Scaling projections from IVUS data. Poiseuille calculations and Fronek's data. See text
- Duplex CFV diameter in a large population study by Fronek; See text
- CIV=Common iliac vein; EIV=external iliac vein; CFV=Common femoral vein
- N/A: Not calculated because of lack of reliable flow estimates.

Ideal Conduit Caliber

\[ F = \Delta P = \frac{1}{2} \frac{d^4}{R^4} \]

\[ F = \Delta P = \frac{1}{8} \frac{d^4}{R^4} \]

\[ F = \Delta P = \frac{(350 \text{ mmHg})^4}{1 \text{ cm}} \]

\[ F = \Delta P = \frac{1}{64} \]

*At 120 cm Length (heart to toe), the ideal diameter is 3.74 cm
Effect of Sideline Capacitance on Pressure

<table>
<thead>
<tr>
<th>Penrose Wall Thickness</th>
<th>Pressure (mmHg) With Sideline Capacitance</th>
<th>Pressure (mmHg) Without Sideline Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ply</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>Two Ply</td>
<td>4.8</td>
<td>3.9</td>
</tr>
<tr>
<td>Three Ply</td>
<td>5.2</td>
<td>5.9</td>
</tr>
<tr>
<td>Four Ply</td>
<td>10</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Control of Peripheral Venous Pressure

<table>
<thead>
<tr>
<th>Central Mechanisms</th>
<th>Clinical Analogue / Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Increased arterial inflow into the limb</td>
<td>• AV Fistula</td>
</tr>
<tr>
<td>• Elevated right atrial pressure</td>
<td>• Congestive Heart Failure</td>
</tr>
<tr>
<td>• Increased intra-abdominal pressure</td>
<td>• Mortal Obesity</td>
</tr>
<tr>
<td>• Iliac vein stenosis</td>
<td>• May-Thurner Syndrome</td>
</tr>
</tbody>
</table>

Peripheral Mechanisms

• Decreased Native Unstretched Caliber
• Decreased Compliance
• Focal Stenosis
• Venous tone
• Post-capillary Inflow

• Mal-development; insufficient upscaling at venous confluence.
• Decreased compliance reduces functional caliber. Organized thrombus can reduce luminal caliber.
• Nearly 2/3 of the general population will have silent iliac vein stenosis.
• Quantitative caliber effect of venous tone is unknown.
• Rate of arterial inflow into the calf is increased in CVD limbs.

Recommended Stent Diameter and post-stent IVUS Area for Different Vein Segments

<table>
<thead>
<tr>
<th>Vessel Segment</th>
<th>Diameter</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIV</td>
<td>16-18 mm</td>
<td>200-254 mm$^1$</td>
</tr>
<tr>
<td>EIV</td>
<td>14 mm</td>
<td>150 mm$^2$</td>
</tr>
<tr>
<td>CFV</td>
<td>12 mm</td>
<td>110 mm$^2$</td>
</tr>
</tbody>
</table>

$^1$ The ideal diameters of 16 mm/254 sq mm may not be achievable in post-thrombosis cases due to tough-fibrotic band underneath the artery. Post stent area of 200 sq. mm is achievable in most.

Open Channel flow like the river dam here is a fluid mechanical analogue of conduit flow like iliac vein stenosis. Reservoir=Peripheral venous bed and Reservoir depth=venous pressure.
O’Shaughnessy Dam, Yosemite National Park, California. It impounds Tuolumne River, forming the Hetch Hetchy Reservoir. There are multiple sluice gates that control outflow.

![Diagram of O'Shaughnessy Dam](image1)

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**Supine Pressures**

- **Arteriole**: 35 mmHg
- **Thorax**: 15 mmHg
- **Abdominal**: 11 mmHg
- **Gravity**: 90 mmHg (125cmH2O)

**Supine Erect**

- **Arterioles**:
  - Pre-Capillary: 0 mmHg
  - Post-Capillary: Partial occlusion
  - Arterial: 15 mmHg

**Bayliss Effect**

![Diagram of Bayliss Effect](image2)
Modeling Venous Pressure

_Seshadri Raju MD.FACS_
_The Rane Center_
_Jackson, MS._

Disclosure

Stock and Royalty: Veniti, Inc.
US Patent: IVUS use in venous disease
US Patent: Venous stent design